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THE RULING AND PERFORMANCE OF A TEN INCH DIFFRACTION GRATING.

By A. A. MICHELSON.

(Read April 22, 1915.)

The principal element in the efficiency of any spectroscopic appliance is its resolving power—that is, the power to separate spectral lines. The limit of resolution is the ratio of the smallest difference of wave-length just discernible to the mean wave-length of the pair or group. If a prism can just separate or resolve the double yellow line of sodium its limit of resolution will be $\frac{5896-5890}{5893}$ or approximately one one thousandth, and the resolving power is called one thousand.

Until Fraunhofer (1821) showed that light could be analyzed into its constituent colors by diffraction gratings this analysis was effected by prisms the resolving power of which has been gradually increased to about thirty thousand. This limit was equalled if not surpassed by the excellent gratings of Rutherford, of New York, ruled by a diamond point on speculum metal, with something like 20,000 lines, with spacing of 500 to 1,000 lines to the millimeter. These were superseded by the superb gratings of Rowland with something over one hundred thousand lines, and with a resolving power of 150,000.¹

The theoretical resolving power of a grating is given as was first shown by Lord Rayleigh by the formula $R = mn$, in which n is the total number of lines, and m the order of the spectrum. An equivalent expression is furnished by

$$R = \frac{l}{\lambda} (\sin i + \sin \theta),$$

¹ The 6½ in. gratings now ruled on the Rowland engine have a much higher resolving power—probably 400,000.

where l is the total length of the ruled surface, λ the wave-length of the light, i the angle of incidence and θ the angle of diffraction, and the maximum resolving power which a grating can have is that corresponding to i and θ each equal to 90° which gives $R = 2l/\lambda$; that is twice the number of light waves in the entire length of the ruled surface.

This shows that neither the closeness of the rulings nor the total number determine this theoretical limit, and emphasizes the importance of a large ruled space.

This theoretical limit can be reached, however, only on the condition of an extraordinary degree of accuracy in the spacing of the lines. Several methods for securing this degree of accuracy have been attempted but none has proved as effective as the screw. This must be of uniform pitch throughout and the periodic errors must be extremely small.

For a short screw, for example one sufficient for a grating two inches in length, the problem is not very difficult, but as the length of the screw increases the difficulty increases in much more rapid proportion. It was solved by Rowland in something over two years.

Since this time many problems have arisen which demand a higher resolving power than even these gratings could furnish. Among these is the resolution of doubles and groups of lines whose complexity was unsuspected until revealed by the interferometer and amply verified by subsequent observations by the echelon and other methods.

Others that may be mentioned in this connection are the study of the distribution of intensities within the spectral "lines"; their broadening and displacement with temperature and pressure; the effect of magnetic and electric fields, and the measurement of motions in the line of sight, as revealed by corresponding displacement of the spectral lines in consequence of the Doppler effect.

All of these have been attacked with considerable success by observations with the echelon, the interferometer and the plane-parallel plate. These methods have a very high resolving power, but labor under the serious disadvantage that adjacent succeeding

spectra overlap, making it difficult to interpret the results with certainty.

Some twelve years ago the construction of a ruling engine was undertaken with the hope of ruling gratings of fourteen inches—for which a screw of something over twenty inches is necessary. This screw was cut in a specially corrected lathe so that the original errors were not very large, and these were reduced by long attrition with very fine material until it was judged that the residual errors were sufficiently small to be automatically corrected during the process of ruling.

The principal claim to novelty of treatment of the problem lies in the application of interference method to the measurement and correction of these residual errors.

For this purpose one of the interferometer mirrors is fixed to the grating carriage, while a standard, consisting of two mirrors at a fixed distance apart, is attached to an auxiliary carriage. When the adjustment is correct for the front surface of the standard, interference fringes appear. The grating carriage is now moved through the length of the standard (one tenth of a millimeter if the periodic error is to be investigated; ten or more millimeters if the error of run is to be determined) when the interference fringes appear on the rear surface. This operation is repeated, the difference from exact coincidence of the central (achromatic) fringe with a fiducial mark being measured at each step in tenths of a fringe (twentieths of a light-wave). As a whole fringe corresponds to one hundred thousandth of an inch, the measurement is correct to within a millionth of an inch.

The corresponding correction for periodic errors is transferred to the worm-wheel which turns the screw; and for errors of run to the nut which moves the carriage. In this way the final errors have been almost completely eliminated and the resulting gratings have very nearly realized their theoretical efficiency.

A number of minor points may be mentioned which have contributed to the success of the undertaking.

(a) The ways which guide the grating carriage as well as those which control the motion of the ruling diamond must be very

true; and these were straightened by application of an auto-collimating device which made the deviation from a straight line less than a second of arc.

(b) The friction of the grating carriage on the ways was diminished to about one tenth of that due to the weight (which may amount to twenty to forty pounds) by floating on mercury.

(c) The longitudinal motion of the screw was prevented by allowing its spherically rounded end to rest against an optically plane surface of diamond which could be adjusted normal to the axis of the screw.

(d) The screw was turned by a worm wheel (instead of pawl and ratchet) which permits a simple and effective correction of the periodic errors of the screw throughout its whole length.

(e) A correcting device which eliminates periodic errors of higher orders.

(f) It may be added that the nut which actuates the carriage had bearing surfaces of soft metal (tin) instead of wood, as in preceding machines. It was not found necessary to unclamp the nut in bringing it back to the starting point.

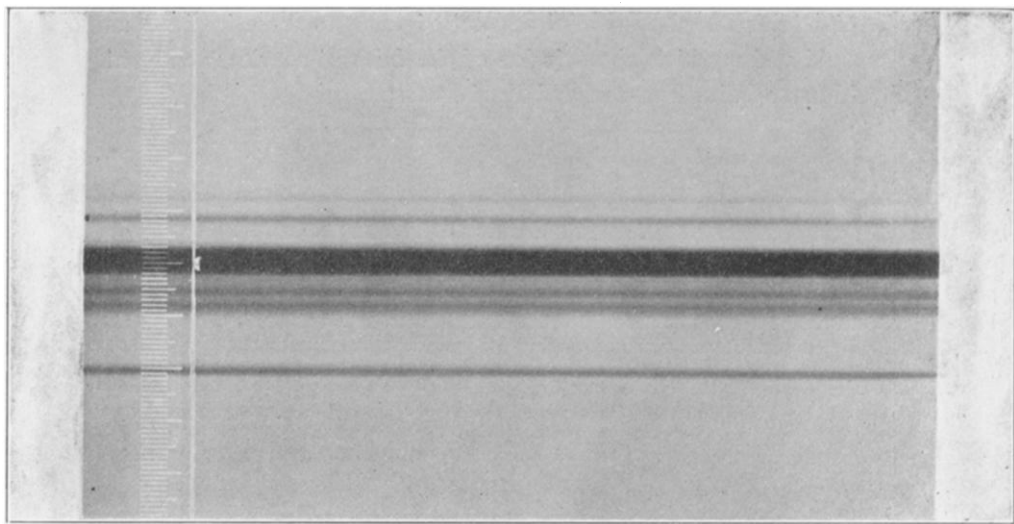
Finally it may be noted that instead of attempting to eliminate the errors of the screw by long continued grinding—which inevitably leads to a rounding of the threads—it has been the main object to make these errors conveniently small; but especially to make them constant—for on this constancy depends the possibility of automatic correction.

The accompanying photograph made with a ten-inch grating, 6th order (actual ruled surface 9.4 inches by 2.8 inches), used in the Littrow form with an excellent 8-inch lens by Brashear, is given in evidence of its performance. The resolving power as shown by the accompanying scale of Angström units is about 450,000. The original negative shows a resolving power of about 600,000. The theoretical value is 660,000.

Doubtless the possibility of ruling a perfect grating by means of the light waves of a homogeneous source has occurred to many—and indeed this was one of the methods first attempted.

It may still prove entirely feasible—and is still held in reserve if

serious difficulty is encountered in an attempt now in progress to produce gratings of twenty inches or more. Such a method may be made partly or perhaps completely automatic, and would be independent of screws or other instrumental appliances.



ENLARGEMENT OF PHOTOGRAPH OF THE GREEN MERCURY LINE λ 5461, taken by H. L. Lemon with 10-inch diffraction grating in sixth order. Scale: 1 division = 0.01 A.U.; ruled surface $9\frac{3}{8}$ in. \times $2\frac{7}{8}$ in., 11,700 lines per inch. Mounted in Littrow form with 8-inch lens by Brashear. Focal length 20 feet.

It may be pointed out that an even simpler and more direct application of light-waves from a homogeneous source is theoretically possible and perhaps experimentally realizable.

If a point source of such radiations send its light-waves to a collimating lens and the resulting plane waves are reflected at normal incidence from a plane surface, stationary waves will be set up as in the Lippman plates; these will impress an inclined photographic plate with parallel lines as in the experiment of Wiener; and the only limit to the resolving power of the resulting grating is that which depends on the degree of homogeneity of the light used. As some of the constituents of the radiations of mercury have been shown to be capable of interfering with difference of path of over

a million waves, such as grating would have a resolving power exceeding a million.

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In addition to the grateful acknowledgment to these institutions I would add my high appreciation of the faithful services rendered by Messrs. Julius Pearson and Fred Pearson.